Facilities for Long Baseline Neutrino Oscillation Studies, Nucleon Decay and Atmospheric Neutrinos

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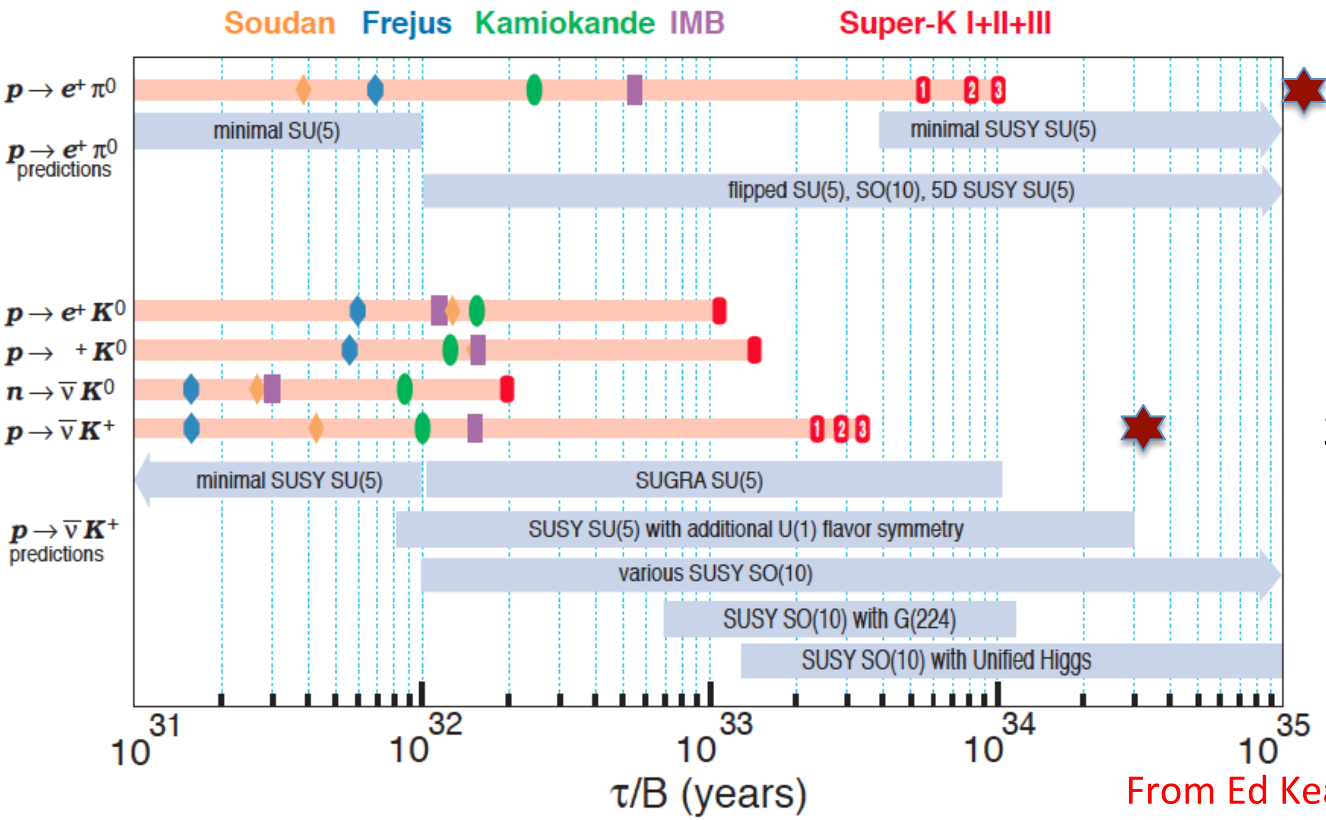
Physics - Long-baseline Neutrino Oscillations

- Current generation of neutrino oscillation experiments have made measurements of two mass-squared differences, Δm^2_{12} and $|\Delta m^2_{23}|$, and now all three mixing angles.
- The remaining unknowns in the three-flavor picture are the mass hierarchy, the CP phase angle δ, and the octant of θ_{23}. Long-baseline neutrino beams of ~GeV energies coupled with large detectors can address all these unknowns.

Physics – Nucleon Decay

- To date, the search for nucleon decay has not yielded any positive evidence.
- The absence of nucleon decay, now extended beyond 10^{34} years lifetime, has provided stringent constraints that must be addressed by any proposed Grand Unified Theory (GUT).
- Additional exposure will probe and constrain these models…**and maybe discover evidence.**

Present Limits and Projected Sensitivity



560 kton Hyper-K

34 kton LBNE

From Ed Kearns

<u>After 10 years operation:</u>

$p \rightarrow e^+ + \pi^0$:
1.3×10^{35} years (90% C.L.)

$p \rightarrow \nu + K^+$:
3.0×10^{34} years (90% C.L.)

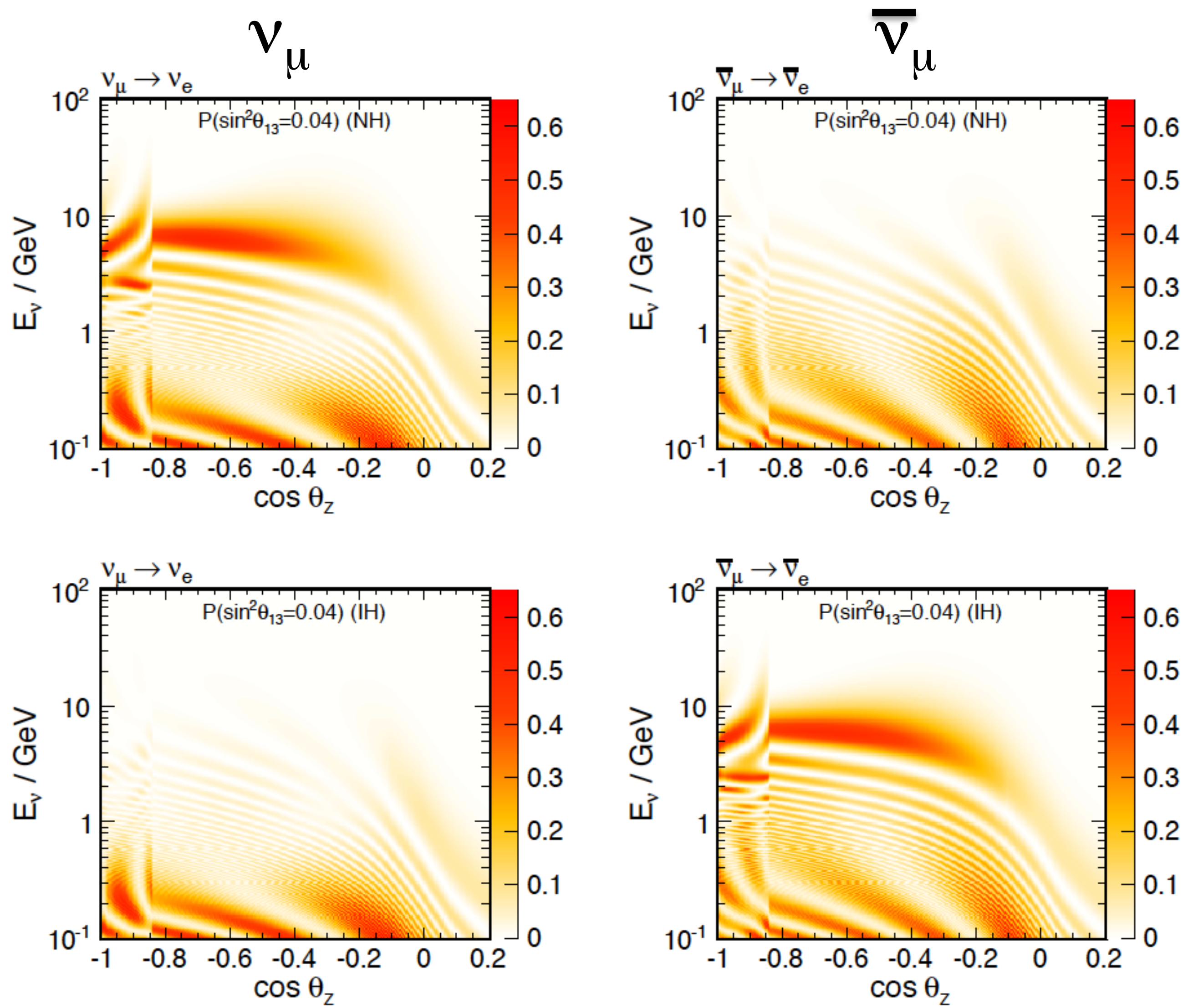
Physics – Atmospheric Neutrinos

- Atmospheric neutrinos are observable in a large underground detector.
- Due to great sensitivity to matter effects, a wide energy range from 100 MeV to 1 TeV, and a wide range of baselines, atmospheric neutrinos are sensitive to all of the currently unknown oscillation parameters and also provide a valuable laboratory for testing exotic models including CPT violation, decoherence, and non-standard interactions (NSI).
- Current experiments are statistics limited.

Oscillation Probabilities for Atmospheric Neutrinos

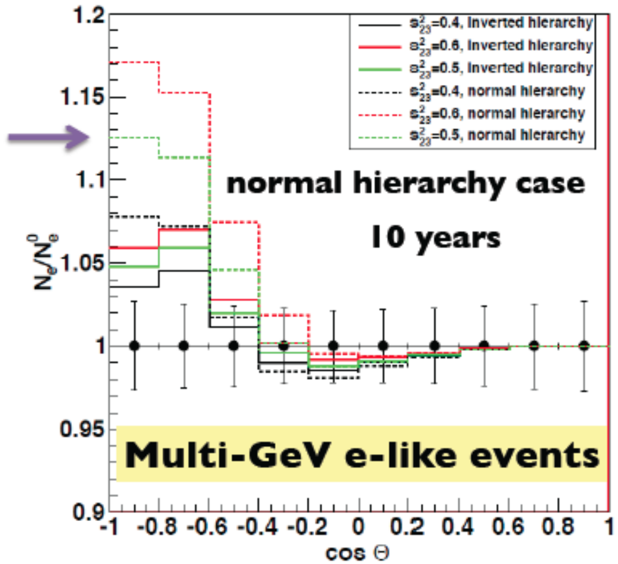
Normal hierarchy

Inverted hierarchy

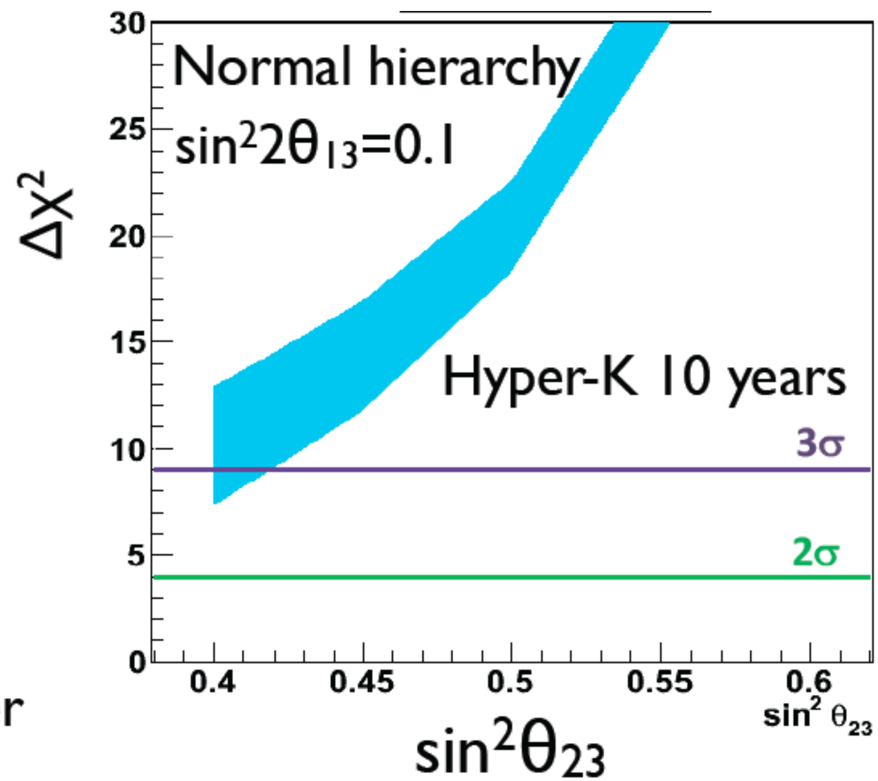


LBNE Science Document: http://arxiv.org/abs/1307.7335

Example: Hierarchy Sensitivity with Atmospheric Neutrinos in Hyper-K



MSW effect in Earth's core
→ resonance effect on either
ν or anti-ν



3σ determination with <10 year observation
(better sensitivity depending on the value of θ_{23})

From Hyper-K Metrics Paper

Synergies/Differences

- There are no definitive predictions for nucleon lifetime.
- Existing limits of $>10^{34}$ years mean that very large detectors (Super-K has limits based on 260 kton yrs) are necessary for a significant improvement in sensitivity.
- Significant progress in the search for nucleon decay requires an underground site to shield from cosmic ray background.
- The large size (cost) coupled with the uncertain result has left progress to be dependent on parasitic operation in large detectors built for another purpose.

Synergies/Differences

- Long baseline experiments are highly motivated/fundable and also require very large detectors.
- Due to tight event timing, overburden is probably not a crucial factor in long baseline experiments, almost any surface or near surface site in a neutrino beam would be usable.

Synergy

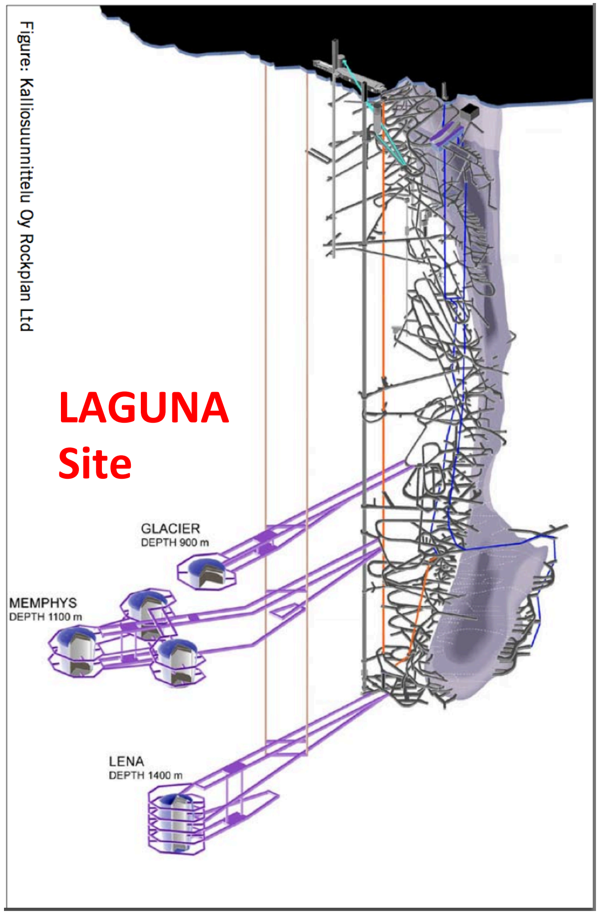
If long baseline detectors are located underground they can also be used for a PDK search, the study of atmospheric neutrinos (and other physics).

Potential Sites

- The overburden requirement for a large nucleon decay or atmospheric neutrino detector depends to some degree on the chosen technology but in general 2000 - 3000 mwe.
- If we assume that a PDK or atmospheric neutrino detector can get funded without the requirement of a neutrino beam for a long baseline component, then there are many potential underground sites.
- Only two sites have been proposed…

Current Proposed Sites for Atmospheric Neutrino Detectors

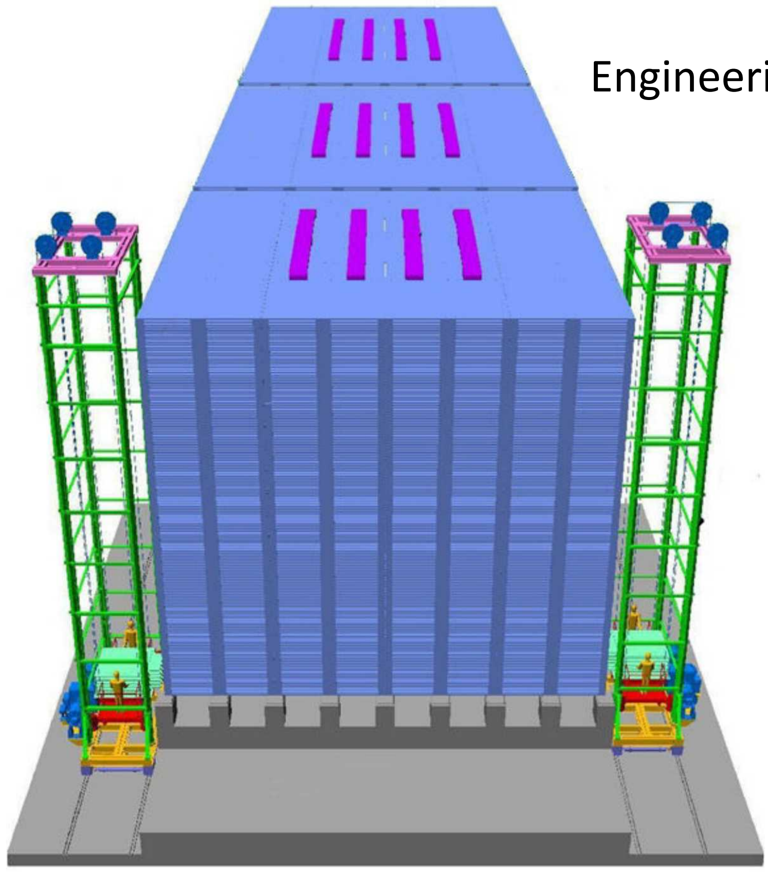
CUPP
Center for Underground Physics
Pyhäsalmi Mine in Pyhäjärvi, Finland
Depth ~ 4000 mwe



India-Based Neutrino Observatory (INO)
ICAL – Magnetized Iron calorimeter – 50 kton

Depth ~ 3500 mwe

Engineering stage



Under Water/Ice Atmospheric Neutrino Detector Sites

These detectors were built to search for extraterrestrial neutrinos.

- – Flux is expected to be small but very high energy.
- – Extremely large volumes required but with high energy detection threshold (>1 Tev) i.e. sparse detector array.

- Subsequent higher density array (IceCube "Deep Core") has been able to observe lower energies and study atmospheric neutrino disappearance.
- Proposed even more dense array e.g. PINGU inside IceCube, could lower the threshold to <10 GeV and be sensitive to the hierarchy through matter effects in the earth.

Sites With a Neutrino Beam

Underground sites with the possibility of a neutrino beam that could potentially accommodate a new large detector include:

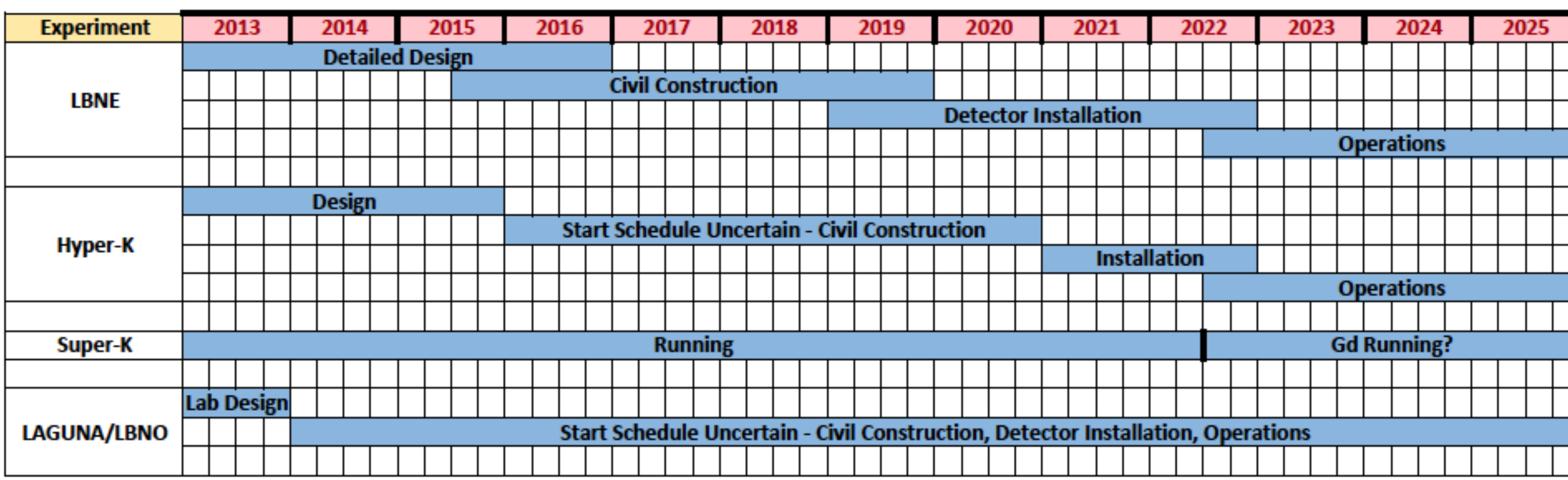
- The Homestake mine in South Dakota, which will be in the LBNE beam
- The Pyhasalmi mine in Finland, which could be in the proposed LBNO neutrino beam
- The Kamioka/Tochibora mine in Japan which is already in the T2K neutrino beam
- The LGNS laboratory in Italy
  - Neutrino beam now ended
- The Soudan site in Minnesota
  - Current NUMI beam

Potential Sites

Facility	Location	Overburden (MWE)	Past/Existing Large Underground Detectors	Proposed/Planned Large Underground Detectors	Beam	References
Homestake	USA	4290	Homestake Chlorine Detector	LBNE (LArTPC)	Future from FNAL	EPJ Plus, 127 9 (2012) 107
Soudan	USA	2090	Soudan II, MINOS		Current from FNAL	www.sudan.unm.edu
LNGS	Italy	3800	LVD, Borexino, ICARUS,OPERA		Current from CERN	EPJ Plus, 127 9 (2012) 109
Pyhasalmi	Finland	3900		MEMPHYS, LENA, GLACIER, MIND	Future from CERN	http://laguna.ethz.ch:8080/Plone
Kamioka	Japan	2700	Kamiokande, Super-K, KamLAND	Hyper-K (Tochibora or Mozumi site)	Current and future beam from J-PARC (T2K, T2HK)	EPJ Plus, 127 9 (2012) 111

Detector Schedules

- Super-K continues to operate underground in the phase I T2K beam.
- Next generation detectors are planned to begin operation in approximately 10 years.
- LBNE is currently the only next generation experiment funded.
  - Current LBNE funding only allows construction on the surface.
  - Additional funding is being sought to allow it go underground.

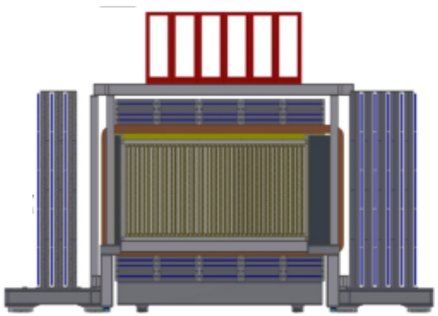


Summary

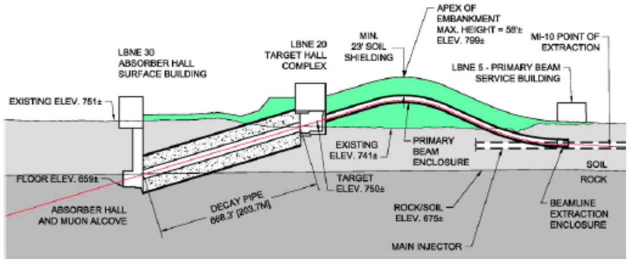
- There is an international effort to search for CP violation in the lepton sector.
- A massive detector in a neutrino beam is required.
- The search for nucleon decay is one of the most important topics in particle physics.
- Atmospheric neutrinos, observable in a large underground detector, are sensitive to all of the currently unknown oscillation parameters.
- The same detector could be used to advance the search for nucleon decay, the study of atmospheric neutrinos and other physics if the detector is located underground.
- This is the plan for Hyper-K and LBNO. It would be a lost opportunity if this condition cannot be satisfied with LBNE.

EXTRA

Long Baseline Neutrino Experiment

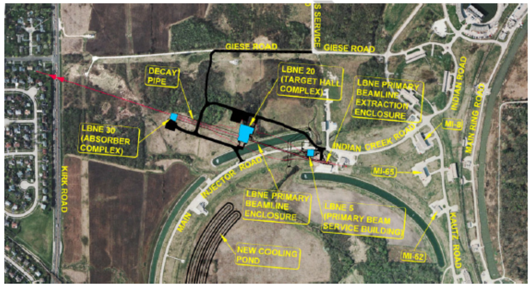


Candidate near detector

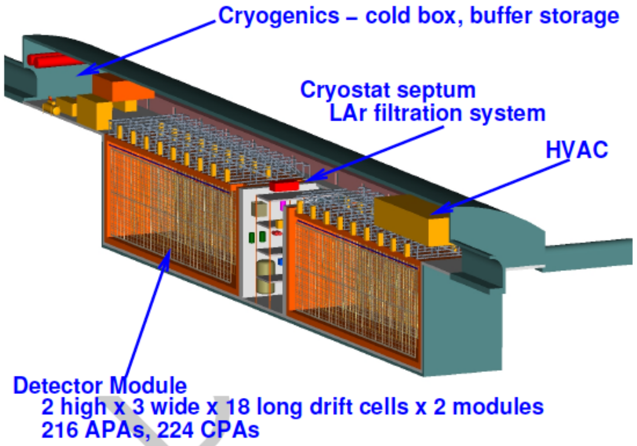


LBNE Beamline

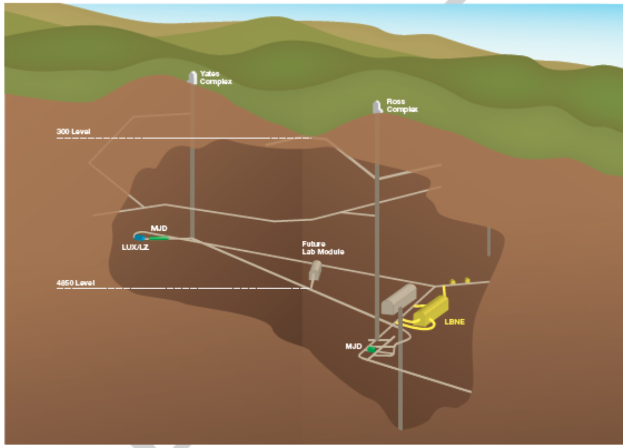
- 5.7^{o} down
- 1,300 km to SURF



LBNE Beamline extraction from Main Injector



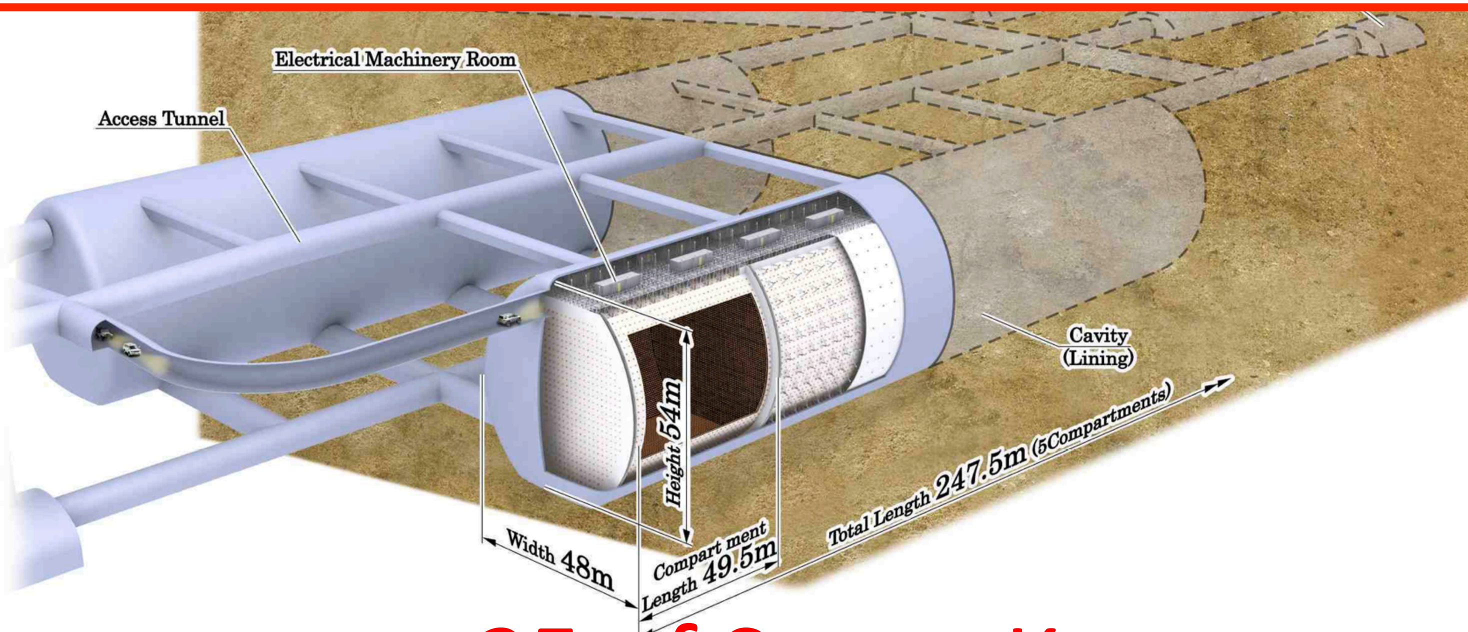
LAr Far detector
34 kT in two modules



SURF facility
Lar detector hall at 4850 level

Hyper-Kamiokande

Total vol.	1 Mton
Fiducial vol.	0.56 Mton (0.056 Mton x 10 compartments)
Photo-sensors	99,000 of 20-inch PMTs for Inner Detector (20% photo-coverage)
	25,000 of 8-inch PMTs for Outer Detector

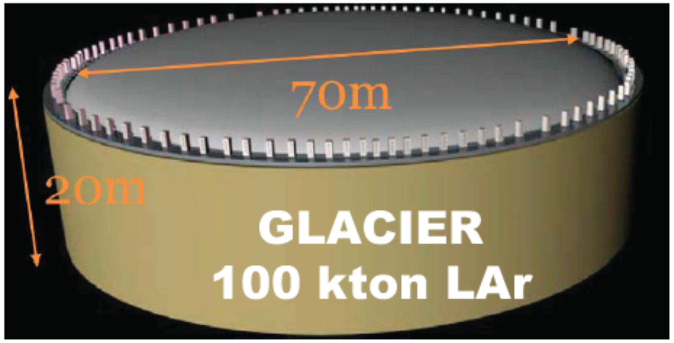


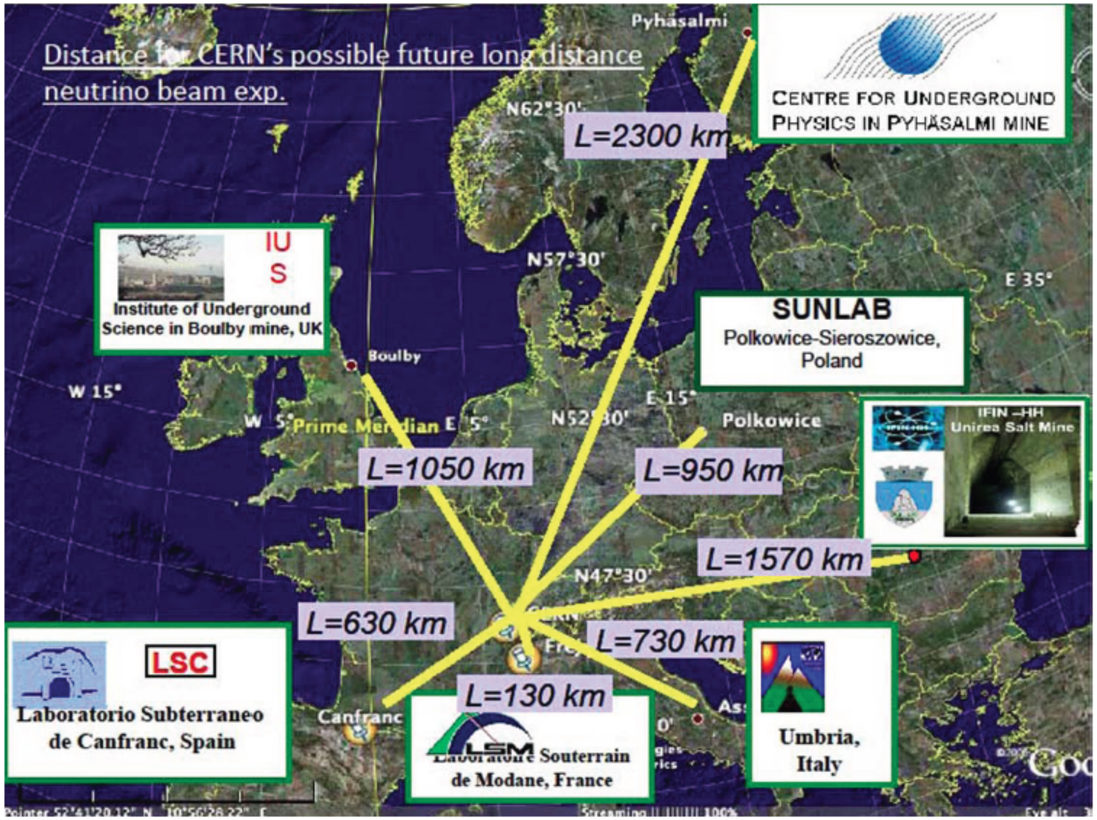
x 25 of Super-K

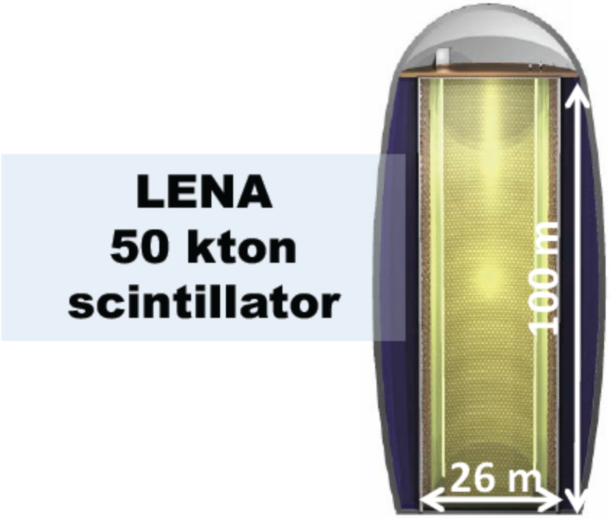
LAGUNA

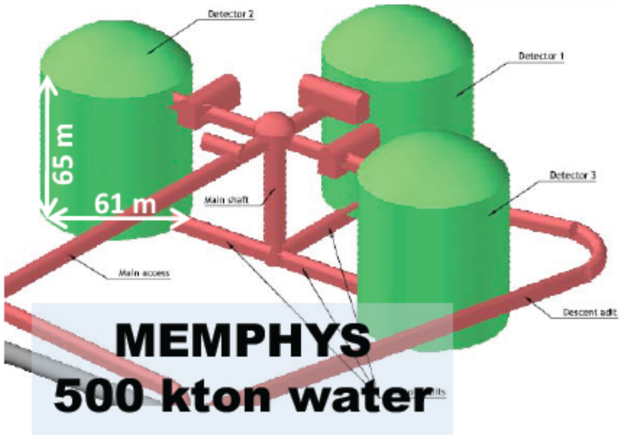
European design study for Large Apparatus for Grand Unification and Neutrino Astrophysics

LAGUNA-LBNO









CUPP
(Center for Underground Physics in Pyhäsalmi Mine in Pyhäjärvi, Finland)

- Pyhäsalmi mine is the biggest operational base metal mine in Finland. It is also the deepest metal mine in Europe.
  - depth 1450 m, ca 4000 metres water equivalent (m.w.e.)
  - the average rock density varies between 2.81-2.83 g/cm^3
  - low radioactivity: U 0.8 ppm, Th 3.2 ppm, K 1.17%, Rn < 70 Bq/m^3 (depends on ventilation)
  - accessibility: a truck road (maximum load size 2.6 m x 2.8 m x 8 m) and a lift all the way down
  - existing infrastructure including buildings, electricity, water pumping and air-conditioning
  - It provides space for scientific experiments:
  - a laboratory and an office on the surface
  - currently active underground research rooms at 90m, 210m, 400m, 660m and 970m
  - new caverns in the new mine (1440 m) can be built if needed